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# Sealing the fate of a fourth generation of fermions

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**Abstract**

The search for the effects of heavy fermions in the extension of the Standard Model with a fourth generation is part of the experimental program of the Tevatron and LHC experiments. Besides being directly produced, these states affect drastically the production and decay properties of the Higgs boson. In this note, we first reemphasize the known fact that in the case of a light and long–lived fourth neutrino, the present collider searches do not permit to exclude a Higgs boson with a mass below the $WW$ threshold. In a second step, we show that the recent results from the ATLAS and CMS collaborations which observe an excess in the $\gamma\gamma$ and $4\ell^{\pm}$ search channels corresponding to a Higgs boson with a mass $M_H \approx 125$ GeV, cannot rule out the fourth generation possibility if the $H \to \gamma\gamma$ decay rate is evaluated when naively implementing the leading $\mathcal{O}(G_F m_{f'}^2)$ electroweak corrections. Including the exact next-to-leading order electroweak corrections leads to a strong suppression of the $H \to \gamma\gamma$ rate and makes this channel unobservable with present data. Finally, we point out that the observation by the Tevatron collaborations of a $\gtrsim 2\sigma$ excess in the mass range $M_H = 115$–$135$ GeV in the channel $q\bar{q} \to WH \to Wb\bar{b}$ can definitely not be accommodated by the fourth generation fermion scenario. All in all, if the excesses observed at the LHC and the Tevatron are indeed due to a Higgs boson, they unambiguously exclude the perturbative fermionic fourth generation case. In passing, we also point out that the Tevatron excess definitely rules out the fermiophobic Higgs scenario as well as scenarios in which the Higgs couplings to gauge bosons and bottom quarks are significantly reduced.

One of the most straightforward extensions of the Standard Model (SM) of particle physics is to assume a fourth generation of fermions: one simply adds to the known fermionic pattern with three generations, two quarks $t'$ and $b'$ with weak–isospin of respectively $\frac{1}{2}$ and $-\frac{1}{2}$, a charged lepton $\ell'$ and a neutrino $\nu'$. Such an extension that we will denote by SM4, besides of being rather simple, has been advocated as a possible solution of some problems of the SM; for recent reviews and motivations for a fourth fermion generation, see Refs. [1–4]. For instance, from a theoretical point of view, it provides new sources of CP–violation that could explain the baryon asymmetry in the universe [3] and, from the experimental side, it might soften some tensions in flavour physics [4].

There are, however, severe constraints on this SM4 scenario. First, from the invisible width of the $Z$ boson, the LEP experiment has measured the number of light neutrinos to be $N_\nu = 3$ with a high precision [5] and, thus, the neutrino of SM4 should be rather heavy, $m_{\nu'} \gtrsim \frac{1}{2}M_Z$, assuming that it has a very small mixing with the lighter SM leptons (not to be produced in association with its light partners which would lead to the stronger limit $m_{\nu'} \gtrsim 100$ GeV). A heavy charged lepton with a mass $m_{\ell'} \lesssim 100$ GeV has also been excluded at LEP2 [5]. In addition, the Tevatron and now the LHC experiments have excluded too light fourth generation quarks. In particular, direct searches performed by the ATLAS and CMS collaborations rule out heavy down-type and up–type quarks with masses $m_{b'} \lesssim 600$ GeV and $m_{t'} \lesssim 560$ GeV [6]. On the other hand, high precision electroweak data severely constrain the mass splitting between the fourth generation quarks while data from B–meson physics constrain their mixing pattern [7]. Finally, the requirement that SM4 remains unitary at very high energies suggests that fourth generation fermions should not be extremely heavy, $m_{q'} \lesssim 500$ GeV [8]. However, this bound should not be viewed as a strict limit but simply as an indication that strong dynamics takes place; a degenerate quark doublet with a mass $m_{q'} \approx 700$ GeV has been considered in a simulation of a strong Yukawa coupling regime on the lattice [9]. Thus, ATLAS and CMS direct searches for $t', b'$ SM4 quarks are closely approaching the masses required by the perturbative unitarity bound and we will assume here that $m_{t'} \approx m_{b'} \pm 50$ GeV $\sim 650$ GeV.

Strong constraints on SM4 can be also obtained from Higgs searches at the Tevatron and the LHC. Indeed, it is known since a long time [10] that in the loop induced Higgs–gluon and Higgs-photon vertices, $Hgg$ and $H\gamma\gamma$, any heavy particle coupling to the Higgs boson proportionally to its mass, as is the case in SM4, will not decouple from the amplitudes and would have a drastic impact. In particular, for the $gg \to H$ process [11, 12] which is the leading mechanism for Higgs production at both the Tevatron and the LHC, the additional contribution of the two new SM4 quarks $t'$ and $b'$ will increase the rate by a factor of $K^{\rm SM4}_{gg\to H} \approx 9$. At leading order in the electroweak interaction, this factor is a very good approximation [13], as long as the heavy quarks are such that $m_{q'} \gtrsim \frac{1}{2}M_H$ which holds true for any $M_H$ value below the TeV scale, given the experimental bounds on the $q'$ masses. The Higgs searches at the Tevatron and the LHC, which are now becoming very sensitive, should therefore severely constrain the SM4 possibility [14]. Indeed, the CDF and D0 experiments for instance exclude a Higgs boson in this scenario for masses 124 GeV $\lesssim M_H \lesssim 286$ GeV by considering mainly the $gg \to H \to WW \to 2\ell 2\nu$ channel [15]. The LHC experiments recently extended this exclusion limit up to $M_H \approx 600$ GeV (at 99% CL) by exploiting also the $gg \to H \to ZZ \to 4\ell, 2\ell 2\nu, 2\ell 2j$ search channels [16].

Nevertheless there are two caveats which might loosen these experimental limits. The first one is that the electroweak radiative corrections to the $gg \to H$ process turn out to be significant [17–19]. For a specific choice of fermion masses which approximately fulfills the electroweak precision constraints [2], $m_{b'} = m_{t'} + 50$ GeV $= m_{\ell'} = m_{\nu'} \sim 600$ GeV, they lead to an increase (decrease) of the cross section at low (high) Higgs masses, $M_H \approx 120$ (600) GeV, by $\approx 12\%$ implying that the exclusion limits above need to be updated and changes in the excluded $M_H$ range up to 10 GeV are expected [19].

The second caveat is that the Tevatron and LHC Higgs exclusion limits in SM4 are only valid for a heavy neutrino $\nu'$. Indeed, if $m_{\nu'} \lesssim \frac{1}{2}M_H$, the Higgs boson will also decay into a neutrino pair [20] and the branching ratio $\text{BR}(H \to \nu'\bar{\nu}')$ can be sizable enough to suppress the rates for the visible channels such as $H \to WW, ZZ$ by which the Higgs is searched for. This is particularly the case for a light Higgs, $M_H \lesssim 160$ GeV, which mainly decays into $b$–quark pairs and $W$ bosons (with one $W$ being virtual). The Higgs total width is small in this case, $\Gamma_H \lesssim 1$ GeV, making the invisible channel $H \to \nu'\bar{\nu}'$ dominant.

Using the program HDECAY [21] in which the Higgs decays in SM4, with all known QCD [13] as well as the leading $\mathcal{O}(G_F m_{f'}^2)$ electroweak and $\mathcal{O}(G_F m_{q'}^2 \alpha_s)$ mixed corrections derived in Ref. [22] have been (naively) implemented[1], we exemplify this feature in Fig. 1 where the Higgs decay branching ratios into $VV$ states normalised to their SM values, $\text{BR}(H \to VV)|_{\text{SM4/SM}}$, are shown as a function of $m_{\nu'}$ for $M_H = 125$ GeV (with this normalisation, these ratios are the same for $V = W$ and $Z$). One first observes that for $m_{\nu'} \gtrsim \frac{1}{2}M_H$, the $\mathcal{O}(G_F m_{\ell'}^2)$ corrections suppress the rate for $H \to VV$ decays while they increase the one for the $H \to \gamma\gamma$ channel. In addition, one can see that for a heavy neutrino $\nu'$, say $m_{\nu'} = 300$ GeV, $\text{BR}(H \to WW, ZZ)$ are suppressed by only a factor of $\approx 5$ compared to their SM values, as a result of the additional $t', b'$ contributions. However, when the $H \to \nu'\bar{\nu}'$ decay channel is kinematically allowed, i.e. for $\frac{1}{2}M_Z \lesssim m_{\nu'} \lesssim \frac{1}{2}M_H$, $\text{BR}_{\text{SM4/SM}}$ is further suppressed and for a given neutrino mass, the suppression factor is comparable to or even larger than the factor $\approx 9$ due to the increase of the $gg \to H$ cross section by the $t', b'$ loop contributions. Thus, the rate for the processes $gg \to H \to WW, ZZ$ can be smaller in SM4 compared to the SM and, hence, the Tevatron and LHC exclusion limits of Refs. [15, 16], which are obtained using these processes, can be evaded[2].

Let us now discuss, in the context of SM4, the excess of events recently observed by the ATLAS and CMS collaborations in the $H \to ZZ \to 4\ell^\pm$ and $H \to \gamma\gamma$ channels corresponding to a SM–like Higgs boson with $M_H \approx 125$ GeV [24] . First of all, for the value $M_H = 125$ GeV, while $\text{BR}(H \to ZZ)|_{\text{SM4/SM}}$ is different from unity as a result of the $\mathcal{O}(G_F m_{f'}^2)$ corrections, the enhancement of the $H \to gg$ rate by the $t', b'$ contributions

[1] For the $H \to gg, f\bar{f}$ and $VV$ decays, the $\mathcal{O}(G_F m_{f'}^2)$ terms when implemented by simply multiplying the couplings $g_{HXX}$ by the electroweak correction $1 + \delta_{EW}^X$, should represent a good approximation [23]. A fourth generation of fermions with degenerate $t', b', \ell', \nu'$ masses $m_{f'} \approx 300$ (600) GeV will suppress the $HVV$ coupling by $\approx 10\%$ (40%) and, hence, the rate for the $H \to VV$ decay (which grows like the square of the coupling) by 20% (80%) [22]. However, in the $H\gamma\gamma$ amplitude, this approximation leads to an unstable result and some reordering of the perturbative series is needed [19] as will be discussed later.

[2] Note that for larger Higgs mass values, $M_H \gtrsim 180$ GeV, the $H \to WW, ZZ$ partial widths become large and these decays are by far dominant and thus not affected by the presence of the $H \to \nu'\bar{\nu}'$ channel. The present Tevatron and LHC exclusion limits are valid in this case, modulo the impact of the electroweak corrections to the production and decay processes which need to be included.

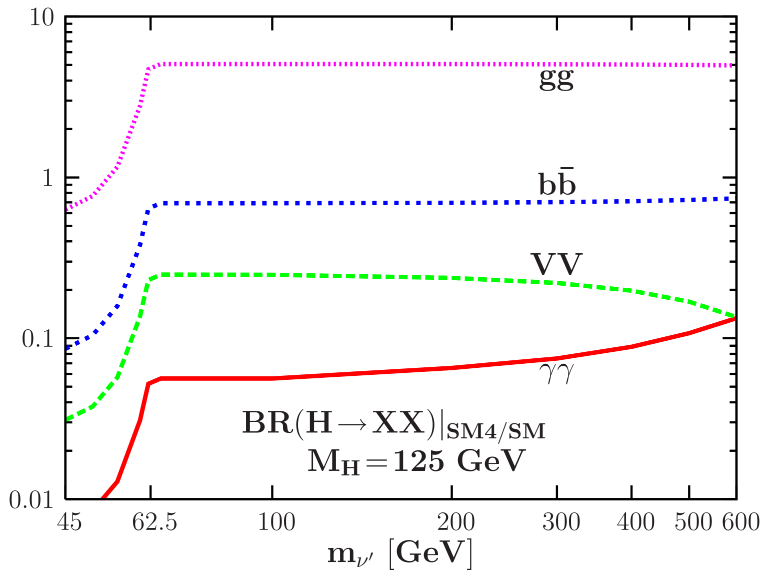


Figure 1: The decay branching ratios of a 125 GeV Higgs particle into $gg, b\bar{b}, \gamma\gamma$ and $VV$ states (with $V = W, Z$) in SM4 normalised to their SM values as a function of the neutrino mass. The heavy quark masses are set to $m_{b'} = m_{t'} + 50$ GeV $= 600$ GeV, while the charged lepton mass is $m_{\ell'} = m_{\nu'} + 50$ GeV. The electroweak corrections are included in a naive way in $H \to \gamma\gamma$.

and eventually the opening of the $H \to \nu' \bar{\nu}'$ mode, the situation is more complicated in the case of $\text{BR}(H \to \gamma\gamma)|_{\text{SM4/SM}}$ as there is another important effect. As a matter of fact, the $H \to \gamma\gamma$ decay is mediated by $W$ boson and heavy fermion loops whose contributions interfere destructively. While this interference is mild in the SM, as the $W$ contribution is much larger than that of the top quark, it is very strong in SM4 because of the additional $t', b'$ and $\ell'$ contributions; the $W$ and all fermion contributions are then very close to each other but opposite in sign. This accidental cancellation makes $\text{BR}(H \to \gamma\gamma)|_{\text{SM4/SM}}$ much smaller than $\text{BR}(H \to VV)|_{\text{SM4/SM}}$ in general, with consequences summarized below.

It is clear from Fig. 1 that in the presence of a relatively light neutrino, $m_{\nu'} \lesssim \frac{1}{2} M_H$, the rates for the $H \to ZZ$ and $H \to \gamma\gamma$ decays are strongly suppressed by a factor that is larger than the one $K^{\text{SM4}}_{gg \to H} \approx 9$ which enhances the $gg \to H$ cross section. Thus, the $\gamma\gamma$ and $4\ell^{\pm}$ excesses corresponding to a SM–like 125 GeV Higgs cannot occur in SM4 when the channel $H \to \nu' \nu'$ is open. The possibility $m_{\nu'} \lesssim \frac{1}{2} M_H$ is thus strongly disfavored.

On the other hand, when this new decay channel is closed, the rates for $H \to VV, \gamma\gamma$ decays increase significantly. If one assumes heavy leptons with $m_{\nu'} \approx m_{\ell'} \approx 600$ GeV (and taking into account the fact that the electroweak corrections decrease $\text{BR}(H \to VV)$ with increasing $m_{\nu'}$), one accidentally obtains a suppression rate $\text{BR}_{\text{SM4/SM}} \approx 7.5$ that is the same in both cases. Recalling that in this case the rate for the main Higgs production process is enhanced by a factor $K^{\text{SM4}}_{gg \to H} \approx 9.5$, one obtains $gg \to H \to \gamma\gamma$ and $4\ell$ rates for $M_H = 125$ GeV that are a $\approx 20\%$ larger in SM4 than in the SM (see also Ref. [25]). It happens that the excesses observed by ATLAS and CMS in the $\gamma\gamma$ channel are stronger than what is expected in the SM, although within the errors bands. Therefore, not only a fourth generation with all heavy fermions having a mass close to $m_{f'} = 600$ GeV could accommodate the excesses observed at the LHC, but it could also explain the substantial rate observed by ATLAS and CMS in the $H \to \gamma\gamma$ signal that has the largest significance.

There is, however, a serious flaw in the discussion above. As mentioned earlier, only the leading $\mathcal{O}(G_F m_{f'}^2)$ terms (and the $\mathcal{O}(G_F m_{q'}^2 \alpha_s)$ ones) [22] are included in the electroweak corrections to $\mathrm{BR}(H \to \gamma\gamma)$ in Fig. 1, by simply multiplying the $W, t$ and $f'$ amplitudes with the relevant correction $1+\delta_{EW}^X$. The exact next-to-leading order (NLO) electroweak corrections have been very recently calculated [19] and, because of the very strong interference between the $W$ and all fermion loop contributions, they have a drastic impact on the $H\gamma\gamma$ vertex. For $m_{f'} \approx 600$ GeV, these corrections suppress $\mathrm{BR}(H \to \gamma\gamma)|_{\mathrm{SM4}}$ by almost an order of magnitude, compared to the case where the $\mathcal{O}(G_F m_{f'}^2)$ corrections are naively implemented in the amplitudes. Nevertheless, it has been shown [19] that by reordering the perturbative series and including subleading $M_H^2/4M_W^2$ terms in the $W$ amplitude, one can reproduce the relative NLO electroweak corrections of the exact result at the percent level. An adapted version of the program `HDECAY` implements this approximation of the full NLO electroweak corrections to the decay $H \to \gamma\gamma$ in SM4 [26].

Using this new version of `HDECAY`, we display in the left–hand side of Fig. 2 the cross section times branching ratio $\sigma(gg \to H) \times \mathrm{BR}(H \to \gamma\gamma)|_{\mathrm{SM4/SM}}$ at $M_H = 125$ GeV as a function of $m_{\nu'} = m_{\ell'}$ for the value $m_{b'} = m_{t'} + 50 = 600$ GeV (the change when varying $m_{b'}$ in the still allowed range 600–700 GeV should be mild). As can be seen, $\sigma(gg \to H) \times \mathrm{BR}(H \to \gamma\gamma)$ in SM4 is a factor of 5 to 10 smaller than in the SM. The increase of $\sigma(gg \to H)$ by a factor of $\approx 9.5$ in SM4 is thus not sufficient for the $\gamma\gamma$ signal to be observed by the ATLAS and CMS experiments, hence excluding the perturbative SM4 scenario if the $\gamma\gamma$ and $4\ell^\pm$ excesses at the LHC are indeed due to a 125 GeV Higgs boson.

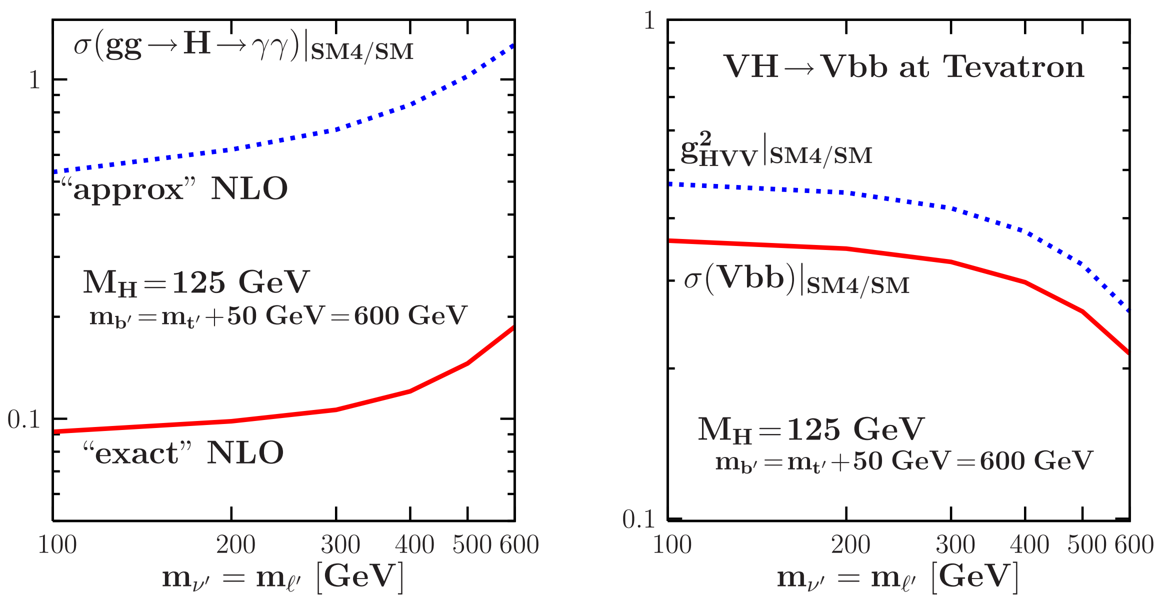


Figure 2: Left: $\sigma(gg \to H) \times \mathrm{BR}(H \to \gamma\gamma)|_{\mathrm{SM4/SM}}$ for a 125 GeV Higgs boson as a function of $m_{\nu'} = m_{\ell'}$ when the leading $\mathcal{O}(G_F m_{f'}^2)$ electroweak corrections are included in a naive way ("approx" NLO) or in a way that mimics the exact NLO results ("exact" NLO). Right: the $HVV$ coupling squared and $\sigma(q\bar{q} \to VH) \times \mathrm{BR}(H \to b\bar{b})$ in SM4 normalized to the SM values.

A final argument against the existence of a fourth generation, and which is theoretically more robust than the argument above based on the LHC $\gamma\gamma$ signal that is subject to large cancellations in the $H \to \gamma\gamma$ amplitude, is provided by the recently updated SM Higgs search by the CDF and D0 collaborations with up to 10 fb$^{-1}$ of data [27]. In this search, a $\approx 2.2\sigma$ excess of data has been observed in the Higgs mass range between 115 and 135 GeV and is mostly concentrated in the Higgs–strahlung channel $q\bar{q} \to VH \to Vb\bar{b}$ with $V = W, Z$; this excess thus strengthens the case for a $\approx$125 GeV Higgs boson at the LHC. In SM4, such an excess cannot occur for the following two reasons. First, compared to the SM, the $HVV$ coupling and hence the production cross sections $\sigma(q\bar{q} \to VH) \propto g^2_{HVV}$ are strongly suppressed by the leading $\mathcal{O}(G_F m^2_{f'})$ corrections (which approximate well the full electroweak NLO corrections in this case [23]) as mentioned earlier. Second, the branching ratio BR$(H \to b\bar{b})$ in SM4 is significantly affected by the presence of the new $t', b'$ quarks and, as shown in Fig. 1, is $\approx$ 30% smaller than in the SM for $M_H \approx 125$ GeV.

The ratio $\sigma(q\bar{q} \to VH) \times \mathrm{BR}(H \to b\bar{b})|_{\mathrm{SM4/SM}}$ is thus much smaller than unity as exemplified in Fig. 2 (right) where it is displayed as a function of $m_{\nu'} = m_{\ell'}$ again for $m_{b'} = m_{t'} + 50 = 600$ GeV. This reduction of the $Vb\bar{b}$ signal rate by a factor 3 to 5 depending on the $m_{\nu'}$ value would make the Higgs signal unobservable at the Tevatron and, therefore, the 2.2 excess seen by CDF and D0, if indeed due to a $\approx$ 125 GeV Higgs boson, unambiguously rules out the SM4 scenario with perturbative Yukawa couplings.

Finally, one should note that the observation of the channel $q\bar{q} \to VH$ with $H \to b\bar{b}$ at the Tevatron would also definitely exclude the fermiophobic Higgs scenario. This possibility has been advocated to explain the excess of events at the LHC in the channel $\gamma\gamma$ (plus additional jets), although the fit probability is not larger than in the SM [28]. The observation of the Tevatron excess in $\ell\nu b\bar{b}$ events can occur only if the decay $H \to b\bar{b}$ is present. In fact, even cases in which the $Hb\bar{b}$ coupling is non–zero but suppressed compared to its SM value are disfavored. Indeed, as the rate $\sigma(WH) \times BR(H \to b\bar{b})$ is, to a good approximation, $\propto g^2_{HWW} \times \Gamma(H \to b\bar{b})/[\Gamma(H \to b\bar{b}) + \Gamma(H \to WW^*)]$ with $\Gamma(H \to WW^*, b\bar{b}) \propto g^2_{HWW,Hbb}$, a suppression by 10%, 50% and 90% of the couplings $g_{Hff}$ would lead to a suppression of $\sigma(Wb\bar{b})$ by, respectively, $\approx$ 5%, 42% and 96%. This is exemplified in Fig. 3 in which the cross section times branching ratio $\sigma(q\bar{q} \to VH) \times \mathrm{BR}(H \to b\bar{b})$, normalized to its SM value, is displayed when the fermionic Yukawa couplings $g_{Hff}|_{\mathrm{FP/SM}}$ are collectively varied from zero (i.e. the pure fermiophobic case) to unity (the SM case).

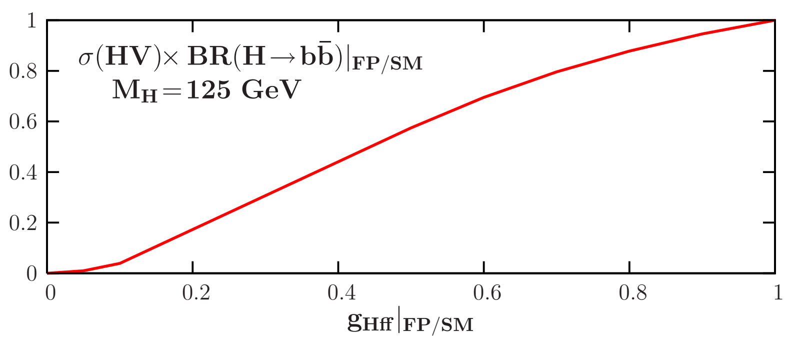


Figure 3: The rate $\sigma(q\bar{q} \to VH) \times \mathrm{BR}(H \to b\bar{b})$ of a 125 GeV Higgs boson normalised to its SM value as a function of the ratio $g_{Hff}|_{\mathrm{FP/SM}}$ of couplings in a fermiophobic Higgs scenario. The program `HDECAY` [21], in which the fermiophobic Higgs scenario is implemented, has been used.

This argument can be extended to many models in which either the $HVV$ coupling or the $H \to b\bar{b}$ branching fraction (or both) are significantly suppressed compared to their SM values as could be the case in, for instance, minimal composite Higgs models [29].

In summary, we have pointed out that while the exclusion bounds on a light Higgs boson, $M_H \lesssim 160$ GeV, in SM4 with a fourth generation can be evaded by assuming a light fourth neutrino, $m_{\nu'} \lesssim \frac{1}{2}M_H$, this possibility is excluded by the observation at the LHC of a Higgs signal at a mass $\approx 125$ GeV in the $\gamma\gamma$ and $ZZ^* \to 4\ell^\pm$ final states. The ATLAS+CMS $4\ell^\pm$ and $\gamma\gamma$ signals are compatible with the SM4 scenario (and larger signal rates than in the SM could even be accommodated) if the leading $\mathcal{O}(G_F m_{f'}^2)$ electroweak corrections are naively included in the $H \to \gamma\gamma$ rate. However, when including the full set of electroweak corrections at next-to-leading order [19], the $\gamma\gamma$ signal is suppressed by an order of magnitude compared to the previous approximation, hence strongly disfavoring a perturbative SM4. Finally, the observation by the CDF/D0 collaborations of a $\gtrsim 2\sigma$ excess corresponding to a Higgs boson with $M_H = 115$–$135$ GeV in the channel $q\bar{q} \to VH \to Vb\bar{b}$ can definitely not be accommodated in SM4. Hence, if the excesses observed at the LHC and the Tevatron are indeed the manifestations of a 125 GeV Higgs boson, the scenario with a perturbative fourth fermionic generation is unambiguously excluded.

*En passant*, we also point out that the pure fermiophobic Higgs scenario cannot accommodate the Higgs signal in the $VH \to Vb\bar{b}$ channel observed at the Tevatron. In fact, many scenarios in which the $Hb\bar{b}$ or $HWW$ couplings (or both) are suppressed compared to their SM values are disfavored if the Tevatron excess is indeed due to a Higgs particle.

**Note added:** On July 4th, 2012 ATLAS and CMS announced new results for the Higgs boson search [30], which has severe implications on the fate of a fourth generation of fermions. Before this announcement a combined fit of electro-weak precision data and Higgs production and decay data yielded the result, that the SM4 is excluded by 3.1 standard deviations [31]. The new data worsens the situation for the SM4 in several points:

1. Both ATLAS and CMS see a $H \to \gamma\gamma$-signal with a statistical significance of more than 4 standard deviations. The total observed rate was higher than expected by the SM (a factor of $1.9 \pm 0.5$ for ATLAS and a factor of $1.56 \pm 0.43$ for CMS). In the SM4 one would expect instead a reduction of the rate by at least a factor of 5 compared to the standard model, see Fig.(2). Thus, both ATLAS and CMS individually see a $H \to \gamma\gamma$-signal, which is about 4 standard deviations away from the expectation of the SM4, which rules out the SM4. As discussed above, the theory prediction for $H \to \gamma\gamma$ in the SM4 suffers from severe cancellations, so one might not want to rely on this decay channel alone.

2. On July 2nd, 2012 also CDF and D0 updated their Higgs search [32] in the Higgs-strahlung channel, discussed above. There the statistical significance increased from 2.6 standard deviations in [27] to 2.9 standard deviations in [32]. At $m_H = 125$ GeV Tevatron finds a signal strength of $1.97^{+0.74}_{-0.68}$, so a little above the SM expectation, while the SM4 predicts values below 0.4, see Fig.(2). Again a stronger indication against the SM4, compared to the status of Moriond 2012.

3. In the SM4 one would expect a sizeable enhancement of the $H \to \tau\tau$ channel, see e.g. [31], which is not observed [30] in the new data. A further argument against the SM4 at the 4 $\sigma$ level.

It is beyond the scope of this paper to make a precise statistical statement about the exclusion of the SM4. Nevertheless, we conclude that the standard model with a perturbative 4th generation and one Higgs doublet is ruled out by this new experimental developments.

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